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(54) **MULTIPLE PATH ACOUSTIC WALL COUPLING FOR SURFACE MOUNTED SPEAKERS**

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(51) **Int. Cl.**

H04R 1/24	(2006.01)
H04R 1/02	(2006.01)

(Continued)

(52) **U.S. Cl.**
CPC ***H04R 1/24*** (2013.01); ***H04R 1/025*** (2013.01); ***H04R 1/22*** (2013.01); ***H04R 1/2857*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC G10K 11/17815; G10K 11/17823; G10K 11/17854; G10K 11/17881;
(Continued)

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Assistant Examiner — Julie X Dang
(74) *Attorney, Agent, or Firm* — Brooks Kushman P.C.

(57) **ABSTRACT**

A surface mounted loudspeaker design is provided that mitigates the interference between direct low frequency (LF) energy and reflected LF energy by breaking the LF energy from an LF driver into multiple paths using one or more of waveguides, driver load plates, and enclosure ports to diffuse the reflected energy and minimize frequency response errors. One or more embodiments of the present disclosure provides a loudspeaker have multiple acoustic exits strategically designed and located to generate, for example, three

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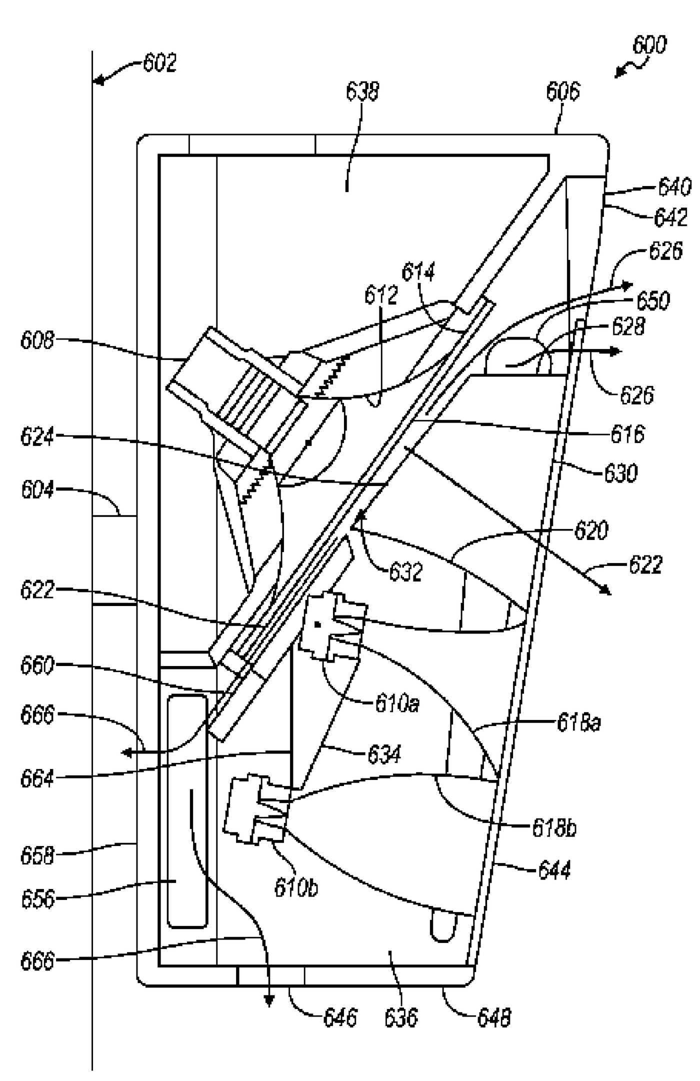

major wave front arrivals—2 source and 1 reflection—at target angles with favorable lag times, mitigating the cancellation notching and frequency errors that occur in conventional loudspeaker designs.

20 Claims, 7 Drawing Sheets

(51) **Int. Cl.**

H04R 1/34	(2006.01)
H04R 5/02	(2006.01)
H04R 1/22	(2006.01)
H04R 3/04	(2006.01)
H04R 9/06	(2006.01)
H04R 1/28	(2006.01)

(52) **U.S. Cl.**
CPC ***H04R 1/345*** (2013.01); ***H04R 3/04*** (2013.01); ***H04R 5/02*** (2013.01); ***H04R 9/063*** (2013.01); *H04R 2201/405* (2013.01)

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CPC . G10K 2210/1282; G10K 2210/12821; G10K 2210/3026; G10K 2210/3028; H04R 1/24; H04R 1/2842; H04R 1/288; H04R 1/345; H04R 1/02; H04R 1/26; H04R 1/2834; H04R 1/2853; H04R 1/323; H04R 1/347; H04R 2201/021; H04R 2499/13; H04R 25/00; H04S 1/002; H04S 3/002
USPC 381/160, 337, 339, 340, 345, 381, 386
See application file for complete search history.

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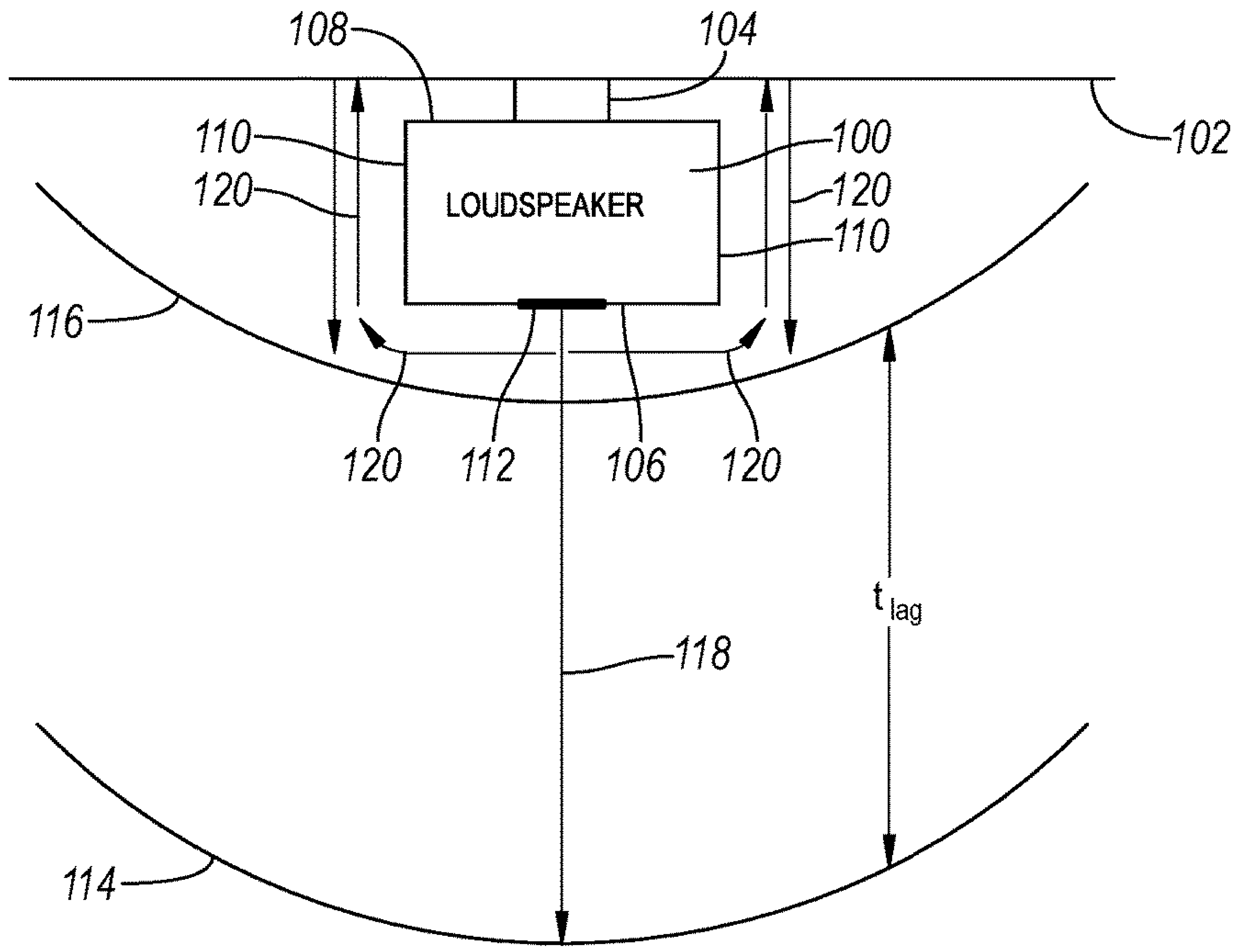

108
104
110
100
102
120
LOUDSPEAKER
120
110
116
120
112
106
120
t_{lag}
118
114

FIG. 1

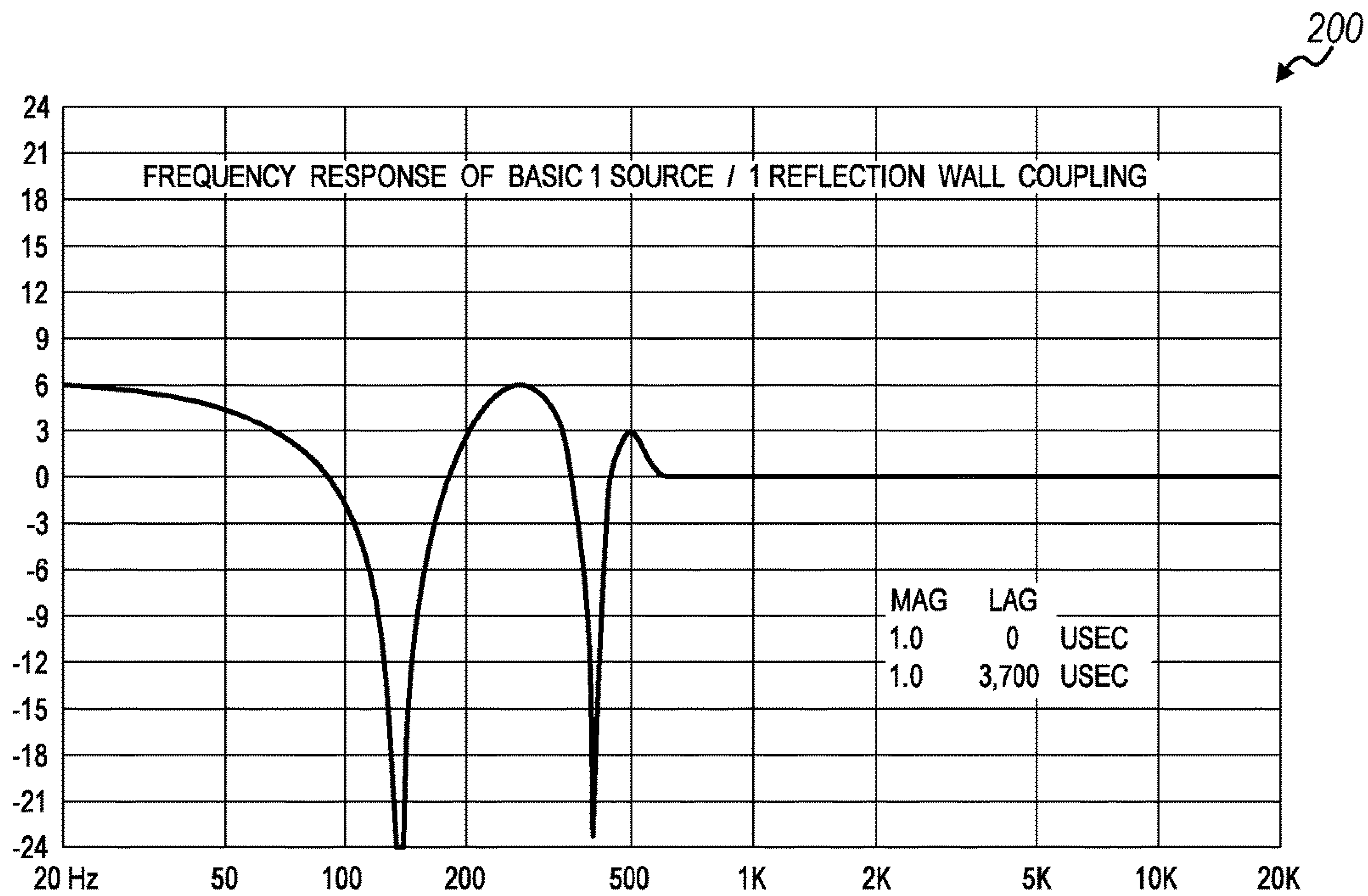

200
FREQUENCY RESPONSE OF BASIC 1 SOURCE / 1 REFLECTION WALL COUPLING
24
21
18
15
12
9
6
3
0
-3
-6
-9
-12
-15
-18
-21
-24
20 Hz
50
100
200
500
1K
2K
5K
10K
20K
MAG LAG
1.0 0 USEC
1.0 3,700 USEC

FIG. 2

300

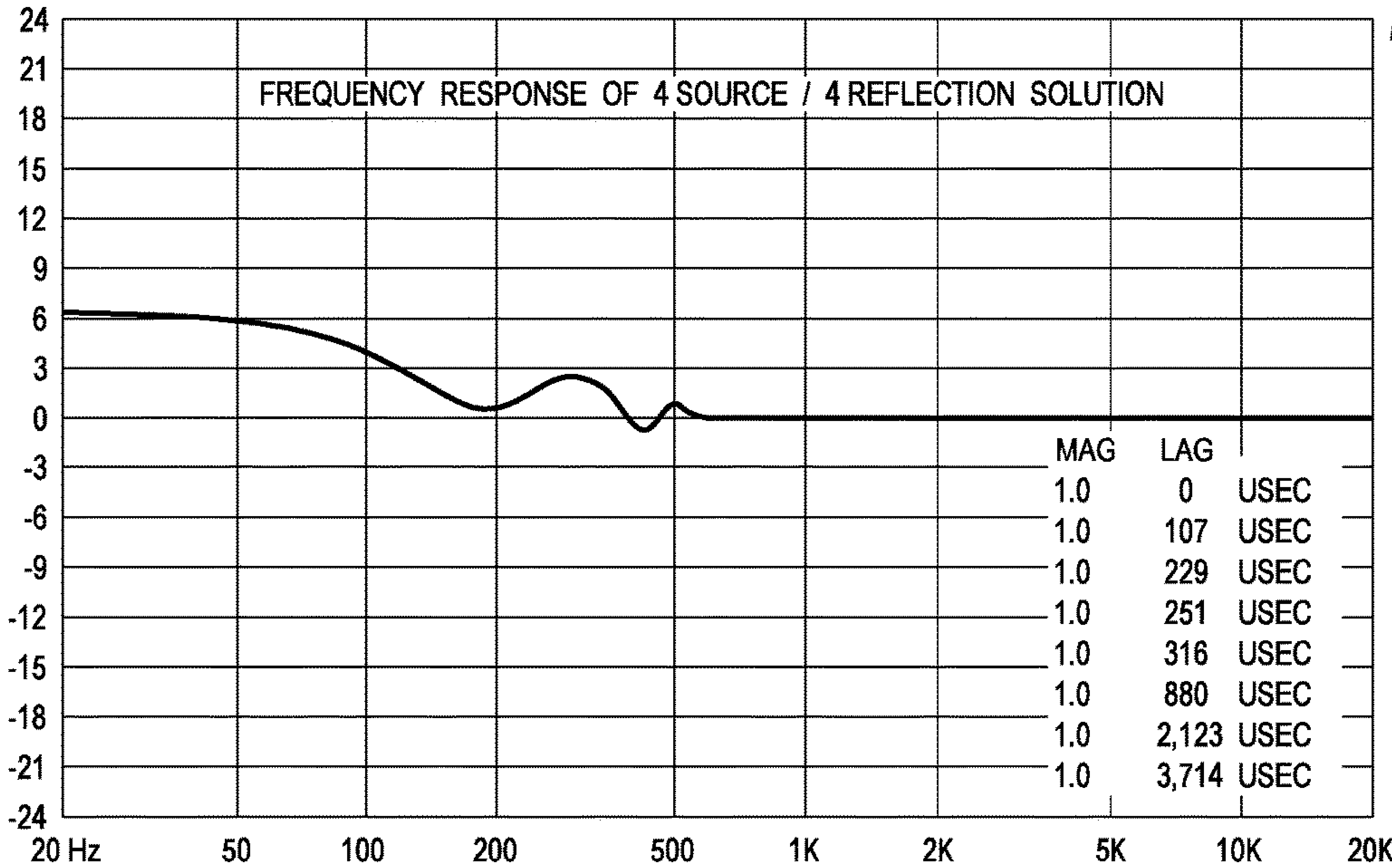


FIG. 3

400

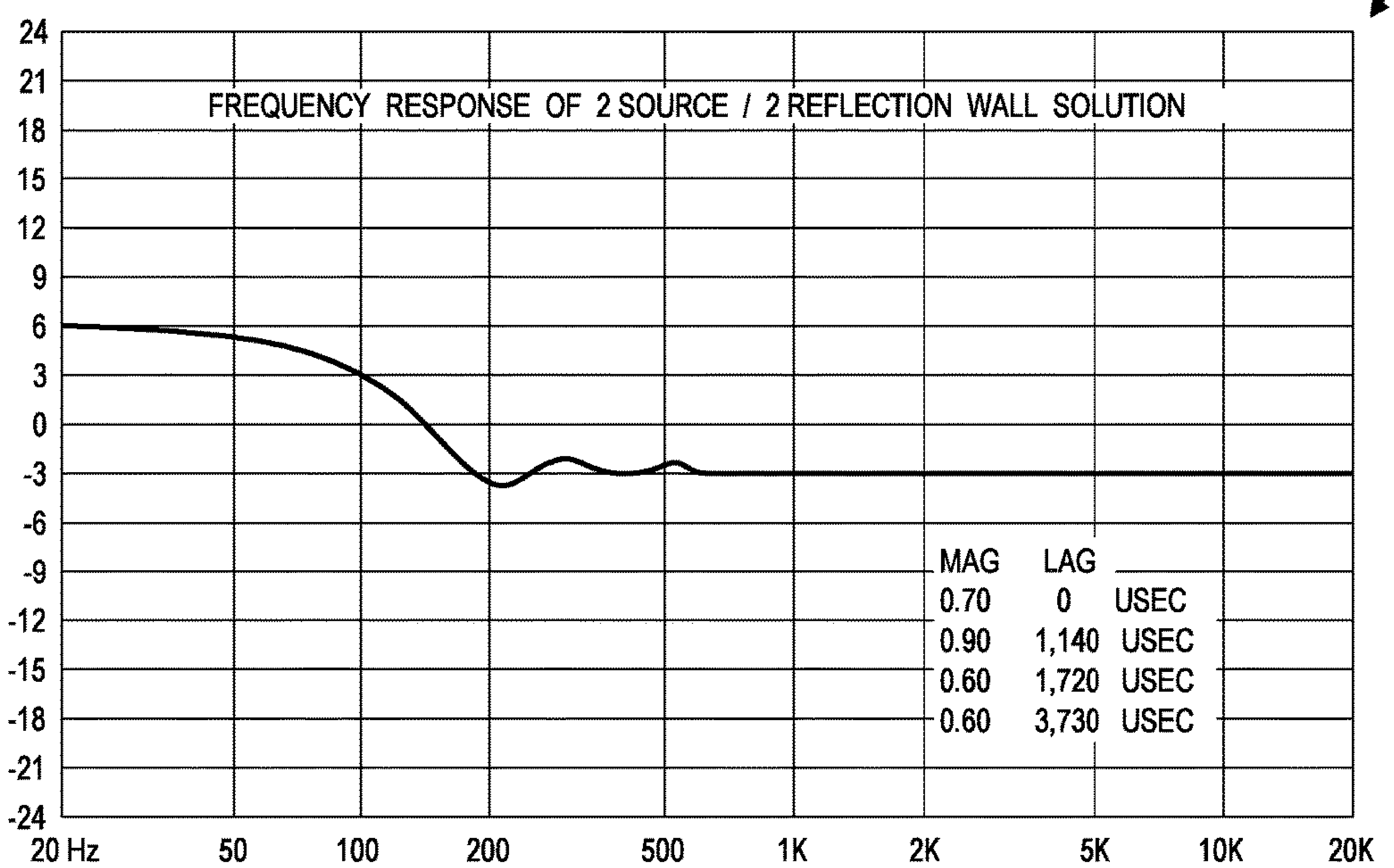


FIG. 4

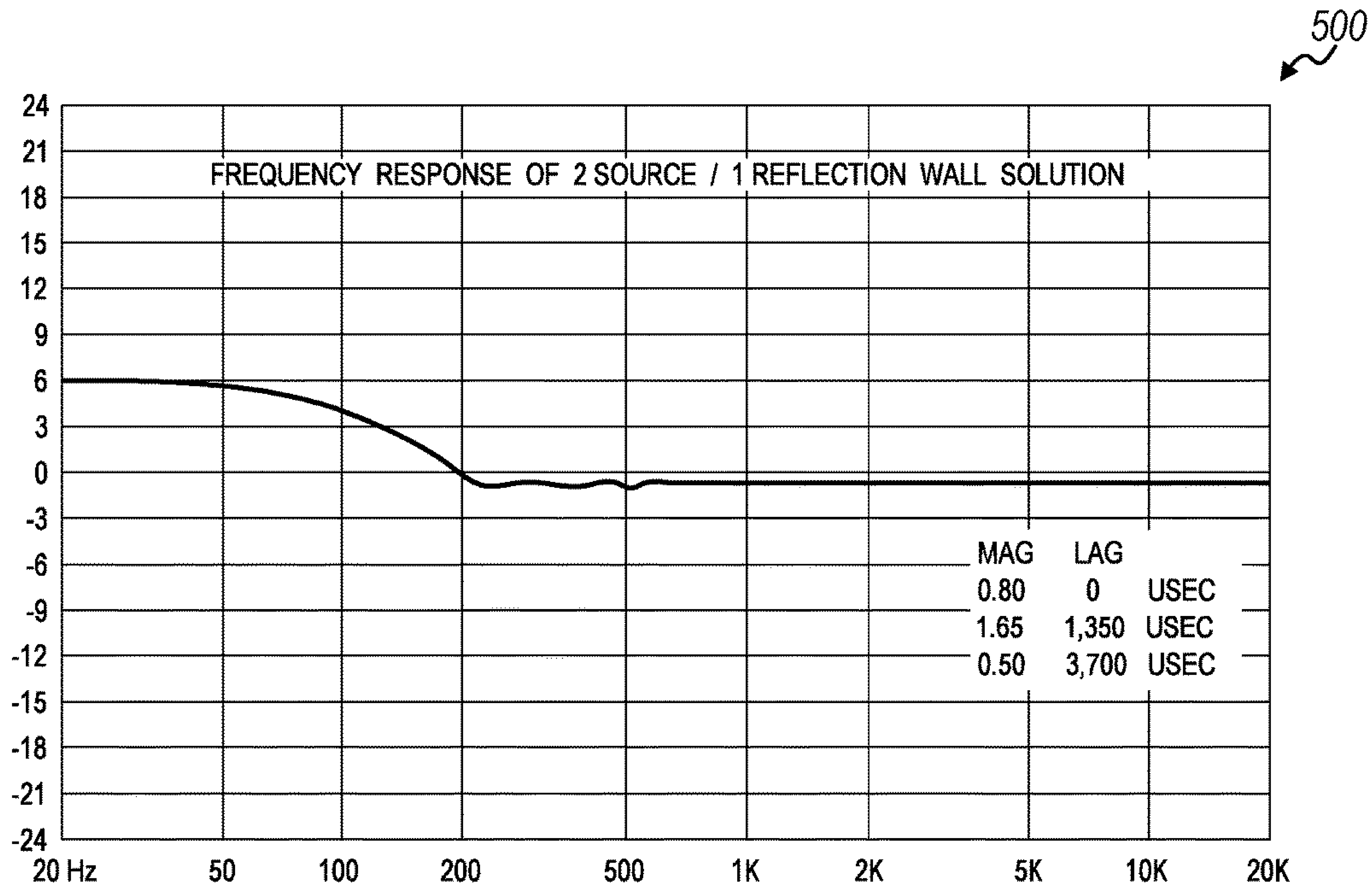

500
FREQUENCY RESPONSE OF 2 SOURCE / 1 REFLECTION WALL SOLUTION
24
21
18
15
12
9
6
3
0
-3
-6
-9
-12
-15
-18
-21
-24
20 Hz
50
100
200
500
1K
2K
5K
10K
20K
MAG LAG
0.80 0 USEC
1.65 1,350 USEC
0.50 3,700 USEC

FIG. 5

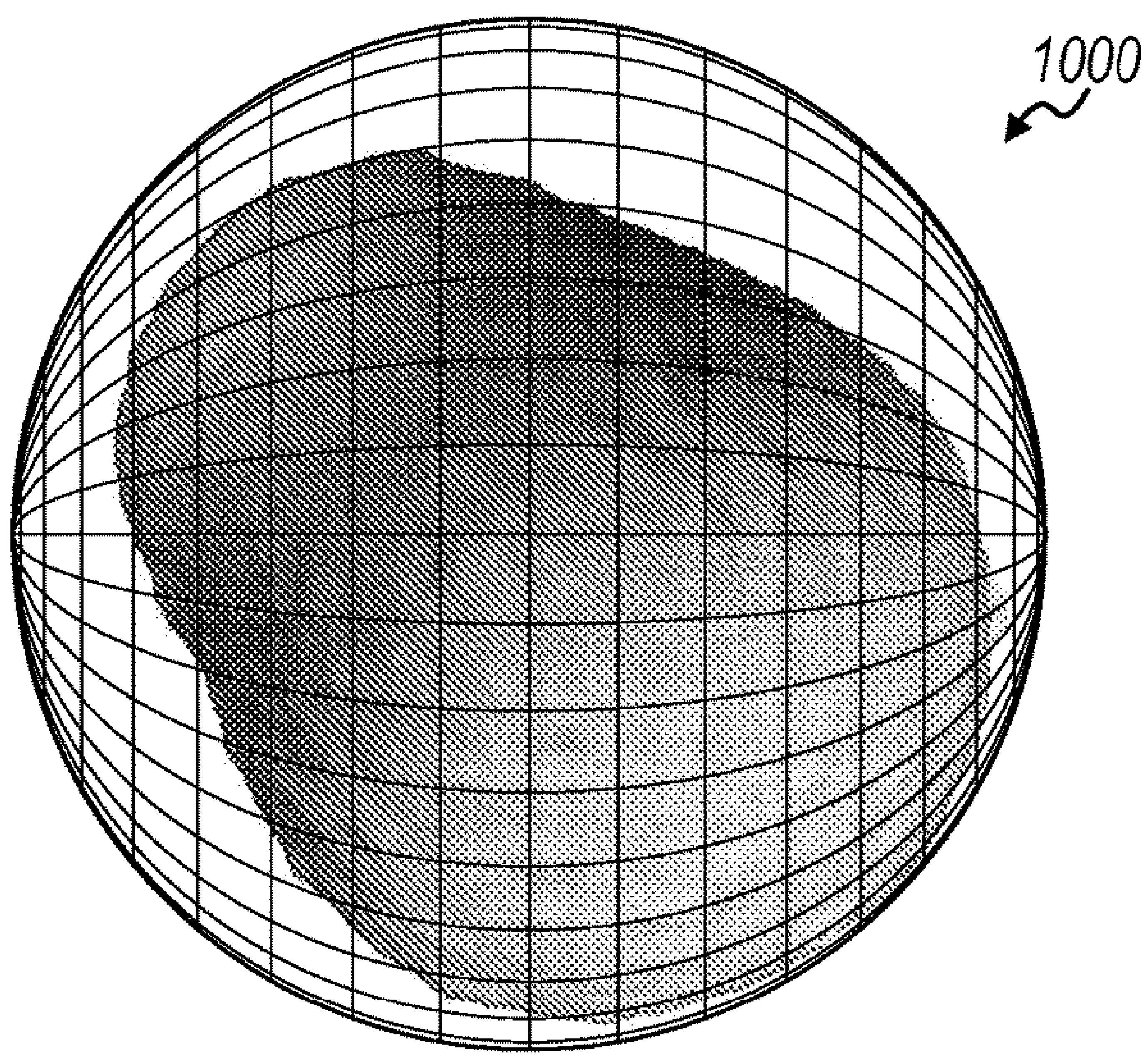
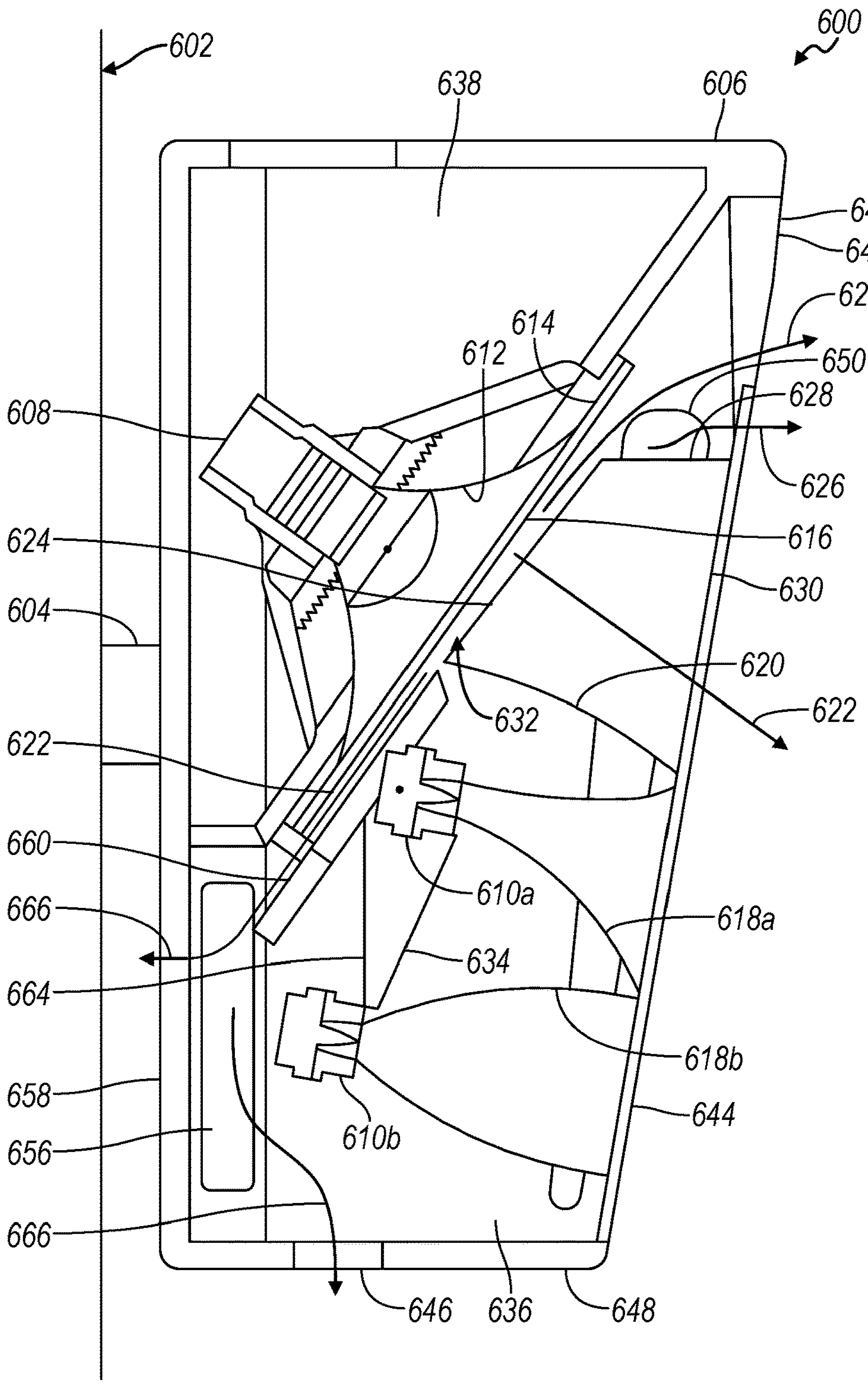

1000

FIG. 10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602
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642
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626
624
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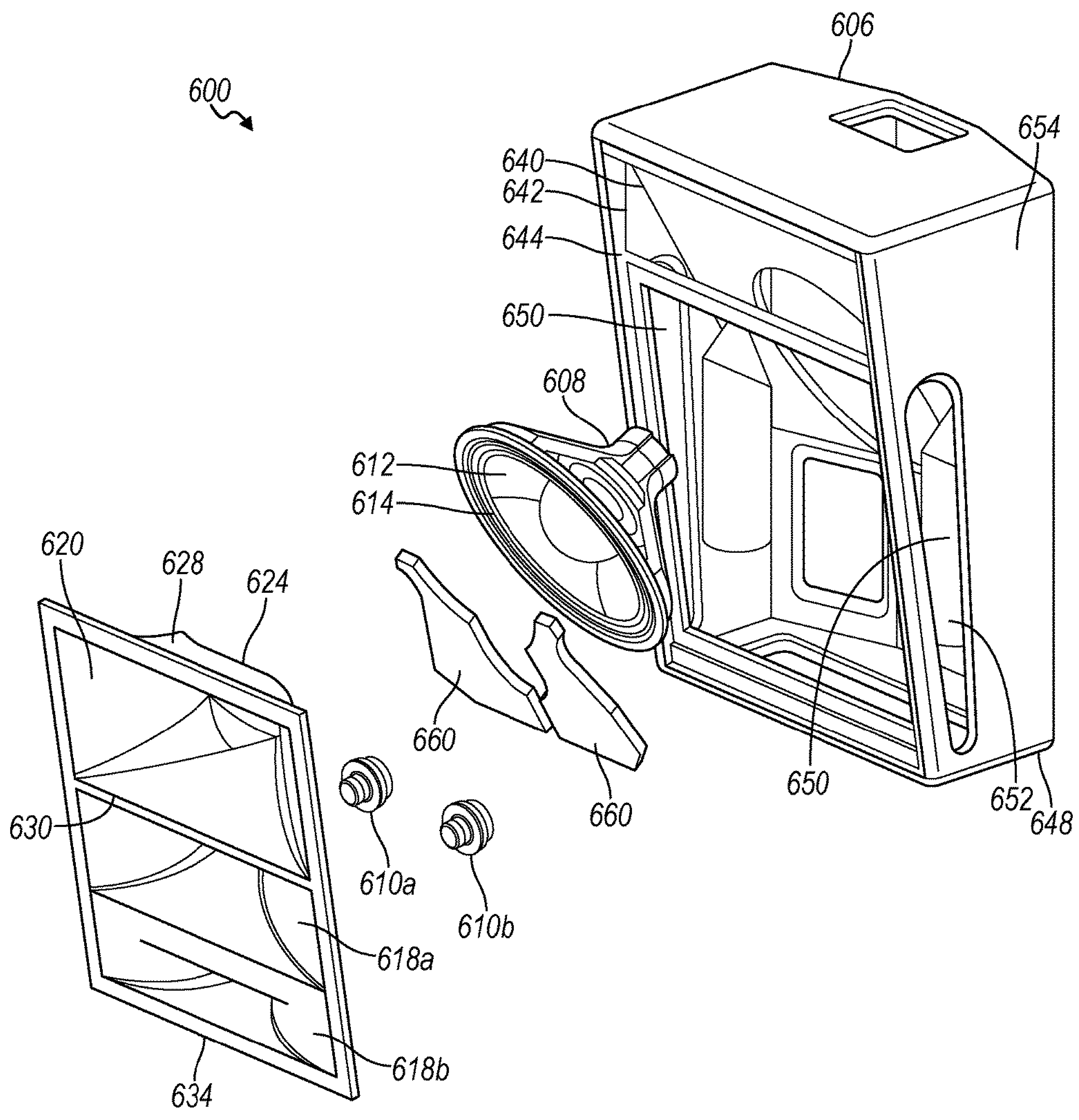
604
620
632
622
622
660
610a
618a
666
634
664
618b
658
644
656
610b
666
646
636
648

FIG. 6



600
606
654
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642
644
650
608
612
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620
628
624
630
660
660
610a
610b
618a
618b
634
650
652
648

FIG. 7

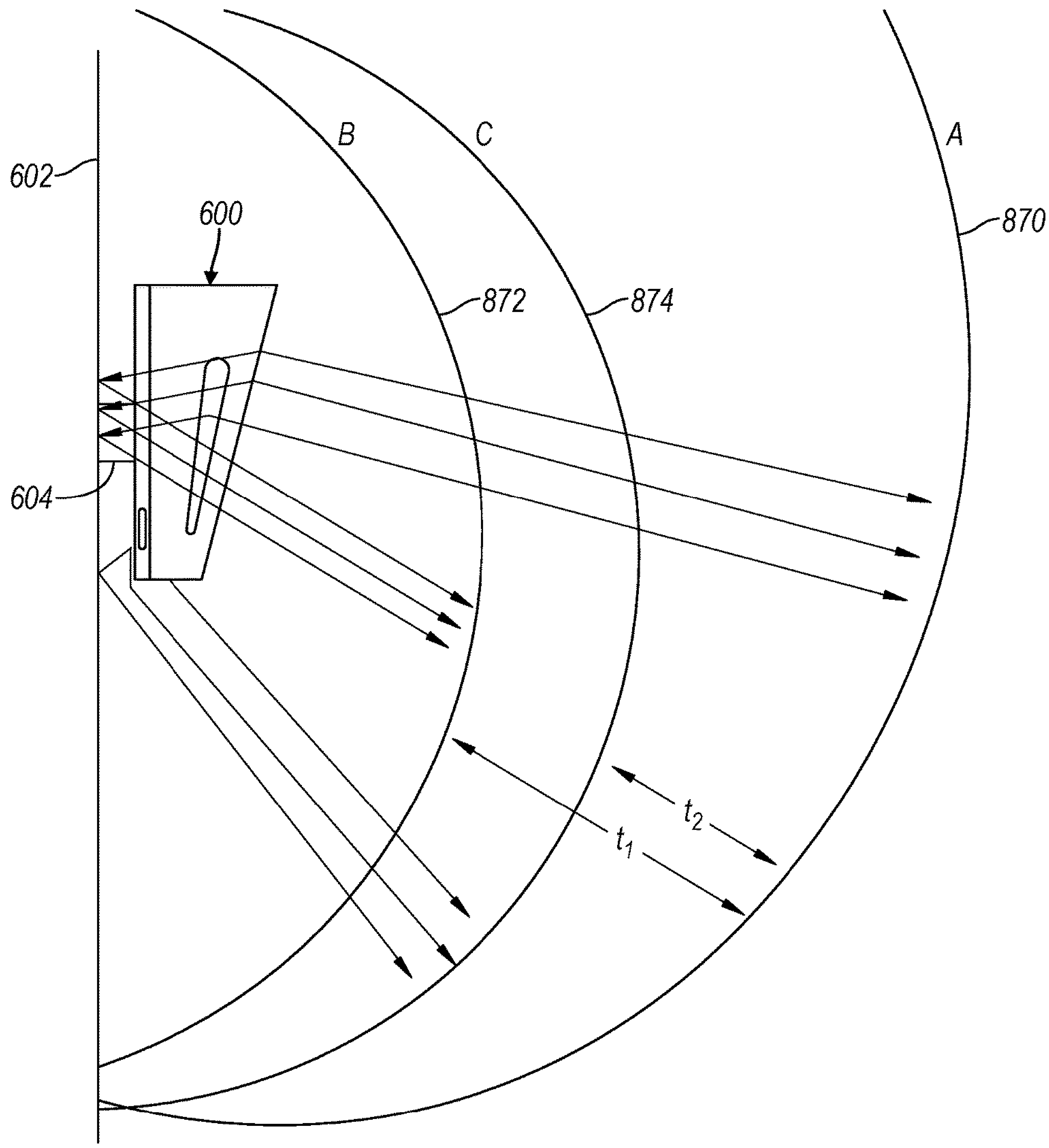

FIG. 8

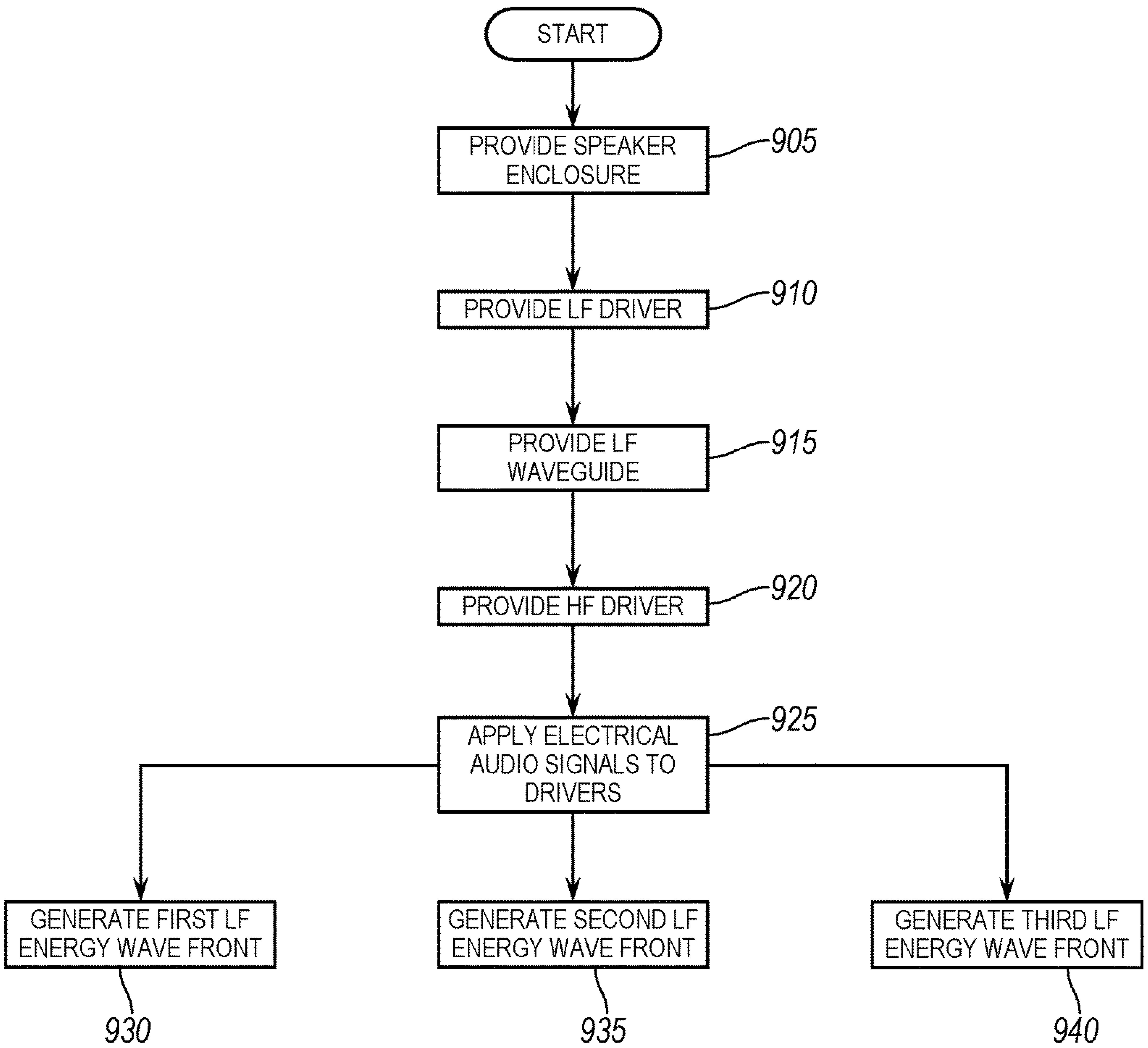
START
PROVIDE SPEAKER ENCLOSURE
905
PROVIDE LF DRIVER
910
PROVIDE LF WAVEGUIDE
915
PROVIDE HF DRIVER
920
APPLY ELECTRICAL AUDIO SIGNALS TO DRIVERS
925
GENERATE FIRST LF ENERGY WAVE FRONT
GENERATE SECOND LF ENERGY WAVE FRONT
GENERATE THIRD LF ENERGY WAVE FRONT
930
935
940

FIG. 9

MULTIPLE PATH ACOUSTIC WALL COUPLING FOR SURFACE MOUNTED SPEAKERS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is the U.S. national phase of PCT Application No. PCT/US2017/013649 filed on Jan. 16, 2017, which claims priority to U.S. provisional application Ser. No. 62/278,952 filed Jan. 14, 2016 and U.S. provisional application Ser. No. 62/278,959 filed Jan. 14, 2016, the disclosures of which are hereby incorporated in their entirety by reference herein.

TECHNICAL FIELD

The present disclosure relates to a multiple path acoustic wall coupling for surface mounted speakers.

BACKGROUND

An acoustic source radiates energy into its surroundings. If this source is an engineered loudspeaker, its radiated energy has an envelope shaped to present uniform energy to the audience. The ability of a loudspeaker to control its radiated energy in this way is diminished at lower frequencies, where wavelengths are larger than the loudspeaker itself, and acoustic energy radiates in all directions equally. In this case, the loudspeaker is said to be omnidirectional.

A surface mounted loudspeaker generates two distinct acoustic energy arrivals, one direct from the transducer and the other reflected from the surface to which it is mounted. The interference of the reflected energy with the direct energy is primarily destructive by creating dramatic frequency response errors. The frequency of these errors is directly related to the time difference between the two energy arrivals at the listener.

SUMMARY

One or more embodiments of the present disclosure is directed to a loudspeaker comprising a speaker enclosure and a low-frequency (LF) driver disposed in the speaker enclosure. The speaker enclosure may be adapted for surface-mounting and include a front surface having at least one front acoustic exit facing a target direction and a rear surface having at least one rear acoustic exit adapted to face a wall surface. The low-frequency (LF) driver may be adapted to emit LF acoustic energy that exits at least the front acoustic exit and the rear acoustic exit. The LF acoustic energy exiting the front acoustic exit and radiating directly in the target direction may form a first LF energy wave front. The LF acoustic energy exiting the front acoustic exit and reflecting off the wall surface may form a second LF energy wave front that lags the first LF energy wave front. The LF acoustic energy exiting the rear acoustic exit and radiating directly in the target direction combined with the LF acoustic energy exiting the rear acoustic exit and reflecting off the wall surface may form a third LF energy wave front that arrives between the first LF energy wave front and the second LF energy wave front.

According to one or more embodiments, the first LF energy wave front may have a magnitude of 0.80. The second LF energy wave front may have a magnitude of 0.50 and lag the first LF energy wave front by 3.70 milliseconds.

The third LF energy wave front may have a magnitude of 1.65 and lag the first LF energy wave front by 1.35 milliseconds.

The speaker enclosure may further comprise at least one side surface having a side acoustic exit. The LF acoustic energy exiting the side acoustic exit and radiating in the target direction may form part of the first LF energy wave front, while the LF acoustic energy exiting the side acoustic exit and reflecting off the wall surface may form part of the second LF energy wave front that lags the first LF energy wave front. The at least one side surface having a side acoustic exit may include two side surfaces, each side surface having the side acoustic exit.

The speaker enclosure may further comprise a bottom surface having a bottom acoustic exit. The LF acoustic energy exiting the bottom acoustic exit and radiating directly in the target direction combined with the LF acoustic energy exiting the bottom acoustic exit and reflecting off the wall surface may form part of the third LF energy wave front that arrives between the first LF energy wave front and the second LF energy wave front.

The loudspeaker may further include an LF waveguide coupled to the LF driver defining a first radiation path for the LF acoustic energy, wherein the at least one front acoustic exit includes the LF waveguide. The at least one front acoustic exit may include a front opening in the speaker enclosure above the LF waveguide. The LF waveguide may have a proximal opening positioned adjacent to the LF driver and extending away from the LF driver to a distal opening to define the first radiation path. The proximal opening may have a proximal opening area that is smaller than a radiating surface opening area to define a second radiation path for the LF acoustic energy around the LF waveguide and out the front opening. The loudspeaker may further comprise a load plate directly in front of a bottom portion of the radiating surface and adjacent the LF waveguide to deflect a portion of the LF acoustic energy along a third radiation path to the rear acoustic exit.

One or more additional embodiments of the present disclosure may be directed to a loudspeaker comprising a speaker enclosure, an LF driver, an LF waveguide, and a load plate. The speaker enclosure may include a front surface having a front acoustic exit, at least one side surface having a side acoustic exit, a rear surface having at least one rear acoustic exit, and a bottom surface having a bottom acoustic exit. The LF driver may be disposed in the speaker enclosure and have a radiating surface adapted to emit LF acoustic energy and a radiating surface opening defined by an outer circumference of the radiating surface. The LF waveguide may define a first radiation path for the LF acoustic energy. The LF waveguide may have a proximal opening positioned adjacent to the LF driver and extending away from the LF driver to a distal opening to define the first radiation path. The proximal opening may have a proximal opening area that is smaller than a radiating surface opening area to define a second radiation path for the LF acoustic energy around the LF waveguide and out the front acoustic exit and the side acoustic exit. The load plate may be directly in front of a bottom portion of the radiating surface and adjacent the LF waveguide to deflect a portion of the LF acoustic energy along a third radiation path to the rear acoustic exit and the bottom acoustic exit.

A target axis of the loudspeaker may be approximately 30° down from horizontal. Alternatively, a target axis of the loudspeaker may be between 30° and 60° down from horizontal.

The loudspeaker may further include at least one high-frequency (HF) driver disposed in the speaker enclosure. The at least one HF driver may include a first HF driver coupled to a first HF waveguide and a second HF driver coupled to a second HF waveguide. The LF waveguide, the first HF waveguide, and the second HF waveguide may be formed from a triple waveguide body. The first HF driver may be disposed in front of the radiating surface of the LF driver and at least partially obstructing the LF acoustic energy emitted by the radiating surface.

One or more additional embodiments of the present disclosure may be directed to a method for radiating sound. The method may comprise providing a speaker enclosure including a front surface having at least one front acoustic exit facing a target direction and a rear surface having at least one rear acoustic exit adapted to face a wall surface. The method may further include providing a low-frequency (LF) driver disposed in the speaker enclosure and adapted to emit LF acoustic energy that exits at least the front acoustic exit and the rear acoustic exit. The method may also include: generating a first LF energy wave front from the LF acoustic energy exiting the front acoustic exit and radiating directly in the target direction; generating a second LF energy wave front that lags the first LF energy wave front from the LF acoustic energy exiting the front acoustic exit and reflecting off the wall surface; and generating a third LF energy wave front that arrives between the first LF energy wave front and the second LF energy wave front from the LF acoustic energy exiting the rear acoustic exit and radiating directly in the target direction combined with the LF acoustic energy exiting the rear acoustic exit and reflecting off the wall surface.

According to one or more embodiments, the first LF energy wave front may have a magnitude of 0.80. The second LF energy wave front may have a magnitude of 0.50 and lag the first LF energy wave front by 3.70 milliseconds. The third LF energy wave front may have a magnitude of 1.65 and lag the first LF energy wave front by 1.35 milliseconds.

Providing a speaker enclosure may further comprise providing the speaker enclosure including at least one side surface having a side acoustic exit. Generating a first LF energy wave front may comprise generating the first LF energy wave front from the LF acoustic energy exiting the front acoustic exit and side acoustic exit and radiating directly in the target direction. Generating a second LF energy wave front that lags the first LF energy wave front may comprise generating the second LF energy wave front from the LF acoustic energy exiting the front acoustic exit and side acoustic exit and reflecting off the wall surface.

Further, providing a speaker enclosure may further comprise providing the speaker enclosure including a bottom surface having a bottom acoustic exit. Moreover, generating a third LF energy wave front that arrives between the first LF energy wave front and the second LF energy wave front may comprise generating the third LF energy wave front from the LF acoustic energy exiting the rear acoustic exit and the bottom acoustic exit and radiating directly in the target direction combined with the LF acoustic energy exiting the rear acoustic exit and the bottom acoustic exit and reflecting off the wall surface.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a top view of a surface-mounted loudspeaker in a room environment illustrating characteristic behavior in the frequency ranges where the loudspeaker acoustic radiation pattern is omnidirectional;

FIG. **2** is an exemplary plot showing the frequency response resulting from a 3.7 millisecond lag time reflected wave of a basic single source/single wall coupling speaker configuration;

FIG. **3** is a plot showing the frequency response resulting from a design with four sources (and their four corresponding reflections) each with equal low-frequency (LF) energy magnitude, according to one or more embodiments of the present disclosure;

FIG. **4** is a plot showing the frequency response resulting from a design with two sources and two reflections, according to one or more embodiments of the present disclosure;

FIG. **5** is a plot showing the frequency response resulting from a design with two sources and one reflection according to one or more embodiments of the present disclosure;

FIG. **6** is a side, cross-sectional view of a loudspeaker, according to one or more embodiments of the present disclosure;

FIG. **7** is an exploded view of the loudspeaker illustrated in FIG. **6**, according to one or more embodiments of the present disclosure;

FIG. **8** is an interpretive side view of the LF wave front arrivals illustrating the characteristic behavior of the loudspeaker in the frequency ranges where the loudspeaker acoustic radiation pattern is omnidirectional, according to one or more embodiments of the present disclosure;

FIG. **9** is a simplified, exemplary flow chart depicting a method for radiating sound, according to one or more embodiments of the present disclosure; and

FIG. **10** is an actual 200 Hz radiation balloon of the loudspeaker depicted in FIGS. **6** and **7**, according to one or more embodiments of the present disclosure.

DETAILED DESCRIPTION

As required, detailed embodiments of the present invention are disclosed herein; however, it is to be understood that the disclosed embodiments are merely exemplary of the invention that may be embodied in various and alternative forms. The figures are not necessarily to scale; some features may be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present invention.

There are numerous situations that require loudspeakers to be surface mounted on a wall. For clarity, surface mounted loudspeakers do not refer to "in-wall" loudspeakers that require cutting into the wall so that the loudspeaker effectively becomes part of the wall. Rather, surface mounted loudspeakers refer to on-wall loudspeakers that are self-contained and use some form of mount to secure them to the wall (or other) surface. The distance between the radiating opening of the loudspeaker and the wall itself becomes a critical dimension. In the frequency ranges where the loudspeaker radiation is omnidirectional, the acoustic interaction of the wall becomes a fundamental part of the loudspeaker characteristic behavior.

FIG. **1** is a top view of a surface-mounted loudspeaker **100** in a room environment. FIG. **1** illustrates a typical surface-mounted loudspeaker characteristic behavior in the frequency ranges where the loudspeaker acoustic radiation pattern is omnidirectional. As shown, the loudspeaker is mounted to a surface **102**, such as a wall, using a mount **104**.

The loudspeaker in this example includes a front surface **106** facing away from the wall surface **102** and in the target direction of an audience, a rear surface **108** that faces the wall surface **102**, and two side surfaces **110**. The loudspeaker in this example further includes a radiating opening **112** in the front surface.

In general and at any given snapshot in time, half of the omnidirectional energy radiated from the loudspeaker **100** is generally directed towards the audience, while the other half radiates towards the wall surface **102**. Typical wall construction forms an acoustic reflector for the low frequency (LF) energy radiated toward the wall surface **102** because most absorption materials are not effective at low frequencies. The resulting energy contains two wave fronts—a direct (or primary) wave front **114** and a reflected wave front **116**. Arrow **118** depicts a radiation path of LF acoustic energy contained in the direct wave front **114**. Arrows **120** depict a radiation path of LF acoustic energy contained in the reflected wave front **116** around a perimeter (e.g., front surface **106** and side surfaces **110**) of the loudspeaker. The direct wave front **114** and reflected wave **116** front are nearly equal in magnitude. However, there is a time lag (t_{lag}) between the reflected wave front **116** and the direct wave front **114** (i.e., the reflected wave front **116** lags the direct wave front **114** in time), as shown in FIG. **1**. The lag relates directly with the speed of sound transit time from the radiating opening **112** of the loudspeaker **100** around the perimeter of the loudspeaker to the wall surface **102** and back. The nature of the reflected wave is a function of the loudspeaker and the acoustic characteristic of the wall surface **102**.

For most traditional wall mounted loudspeakers in, for example, the professional cinema surround loudspeaker product class, the lag time between the direct wave front and the reflected wave front is typically in a range of 1-5 milliseconds. The actual lag time depends on the size of the mount and the size of the loudspeaker. For smaller class surface-mounted speakers, the lag time may be smaller. A 1-5 millisecond lag corresponds to 14-68 inch pathlength delta (i.e., the distance between the direct and reflected wave fronts). In or around this time range, the resulting sound experience may be affected negatively with certain frequencies being canceled out and others being accentuated. In the case of the canceled frequencies, electronic equalization cannot resolve the issue.

FIG. **2** is an exemplary plot showing the frequency response **200** resulting from a 3.7 millisecond lag time reflected wave of a basic single source/single wall coupling speaker configuration, such as is described with respect to FIG. **1**. The term "source," for purposes of this description, refers to any speaker element that radiates sound. A source can be either an acoustic exit (i.e., radiating opening) or a separate radiating element (called a driver). FIG. **2** shows the cancelled frequencies near 150 Hz and 400 Hz. There is an energy peak near 300 Hz. The primary wave front, without the reflection energy, would ideally be a flat line at 0 dB in this simulation. Thus, the reflected energy creates both the cancellations and the peaks. For reference, all simulations are intentionally made "flat" above 500 Hz to simplify the discussion.

There is benefit from the reflected energy when the lag times are relatively small in comparison to the wavelengths involved. When this is the case, the effective output of the loudspeaker is nearly doubled as the audience now receives all of the omnidirectional energy. This is evident from the frequency response curve in FIG. **2** for those frequencies below 60 Hz. One or more embodiments of the present disclosure utilize this property to resolve the cancellation problem by breaking the LF acoustic energy into multiple arrivals. Instead of a singular source, the loudspeaker design according to the present disclosure may use multiple sources in strategic locations on the speaker enclosure. The loudspeaker design of the present disclosure generates a series of wave fronts, both direct and reflected, with lag times between them strategically chosen to mitigate any discernible cancellations.

The loudspeaker design used to achieve a series of direct and reflected wave fronts having relatively small lag times sufficient to resolve the frequency cancellations can be executed in several different ways. According to one or more embodiments, the use of redirected energy from a single driver may be employed. According to one or more alternate embodiments, multiple drivers may be employed. Both designs can achieve similar results with the multiple driver implementations having the most design flexibility.

The energy arrival lag times and their individual energy magnitudes cannot be arbitrary for good performance. With mathematical similarities to diffusion number theory, only certain combinations actually smooth the response and avoid severe cancelations and peaks. A computer optimizer routine may be employed to provide good results. Several simulations created using the optimizer routine and an actual product are shown in FIGS. **3-5**. The three simulation solutions presented are based on different design variables and each provides different results. The corresponding magnitudes and lag times for each source or reflection is shown on each frequency response graph. All simulations are based on the same enclosure size and shape as modeled in the discussion above. In each case, new sources (and their associated wall reflections) are added with optimized magnitudes and lag times to mitigate the cancellation notches. Therefore, the primary LF acoustic energy and its 3.7 millisecond reflection are maintained in each solution.

FIG. **3** is a plot showing the frequency response **300** resulting from a design with four sources (and their four corresponding reflections) each with equal LF energy magnitude. This solution has the desirable property that there is only 6 dB differential between coherent summation and incoherent summation, which is a best case scenario. Coherent summation occurs when the wavelengths between summing energies are within a ¼ wavelength (e.g., everything below approx. 75 Hz in this scenario). Incoherent summation occurs when wavelengths of summing energies are more than ¼ wavelength (e.g., everything above approx. 100 Hz in this scenario). Executing a design with four sources and reflections with the level of precision required may be very difficult, but not impossible. The solutions simulated in FIGS. **4** and **5** may be simpler in nature and assume two sources, a primary and a secondary, which are considered practical and effective.

FIG. **4** illustrates a second solution showing the frequency response **400** resulting from a design with two sources and two reflections. The lag times shown are achievable if one source is on the front surface of the loudspeaker and the second is on the rear surface of the loudspeaker. This solution has 9 dB differential between coherent and incoherent summation, which could be useful in some designs.

FIG. **5** illustrates a third solution showing the frequency response **500** resulting from a design with two sources and one reflection. This solution is achievable with one source on the front surface of the loudspeaker and one source on the rear surface of the loudspeaker. In this case, the mount distance and location of the rear source are such the direct energy and its reflection are indistinguishable (e.g., <100 microsecond lag time). The summation of the direct energy and reflected energy will naturally be a factor 2× if the energies are truly coherent, which tracks with the magnitude shown. The overall response is very smooth and the 7 dB differential between coherent and incoherent summation is very good.

FIGS. **6** and **7** show details of an exemplary loudspeaker **600** employing the solution simulated in FIG. **5**. In particular, FIG. **6** is a side, cross-sectional view of the loudspeaker **600**, while FIG. **7** is an exploded view of the loudspeaker **600** illustrated in FIG. **6**. According to one or more embodiments, the loudspeaker **600** may be a professional cinema surround loudspeaker. However, other speaker classes may employ the various design techniques described herein and achieve similar results. Typical of professional cinema surrounds, the loudspeaker may surface mount to a wall surface **602** (e.g., a theater wall) with a mount **604** holding it between 4-8 inches off the wall. The loudspeaker **600** may be a two-way loudspeaker including a speaker enclosure **606**, an LF driver **608** and at least one high-frequency (HF) driver **610**. As shown, the at least one HF driver **610** may include a first HF driver **610***a* and a second HF driver **610***b*, both adapted to emit HF acoustic energy. However, the two-way loudspeaker design according to the present disclosure may be employed using only a single HF driver.

The LF driver **608** may include a radiating surface **612**, sometimes referred to as a cone or diaphragm, adapted to emit LF acoustic energy. The radiating surface **612** moves like a piston to pump air and create sound waves in response to electrical audio signals. An outer circumference **614** of the radiating surface **612** may define a radiating surface opening **616** having a radiating surface opening area.

The LF driver **608** and the two HF drivers **610** may have corresponding waveguides to aid in directing acoustic energy. The first HF driver **610***a* may be physically coupled to a first HF waveguide **618***a* while the second HF driver **610***b* may be physically coupled to a second HF waveguide **618***b*. According to one or more embodiments of the present disclosure, the loudspeaker design may employ an LF waveguide **620** that is smaller than a traditional low frequency waveguide. The LF waveguide **620** defines a first radiation path **622** for the LF acoustic energy. The LF waveguide **620** may include a proximal opening **624** positioned adjacent to the LF driver **608** (coupling to the driver) that may be considerably smaller than the radiating surface **612** of the LF driver **608**. The proximal opening **624** of the LF waveguide **620** may define a proximal opening area. Accordingly, the proximal opening area may be smaller than the radiating surface opening area. Because the proximal opening area may be smaller than the radiating surface opening area, this defines at least a second radiation path **626** for the LF acoustic energy around an outer surface **628** of the LF waveguide **620**.

The LF waveguide **620** may extend away from the LF driver **608** to a distal opening **630** (coupling to free air) defining the first radiation path **622** therethrough. The distal opening **630** may define a distal opening area and be sized appropriate to waveguide design practice, as understood by one of ordinary skill in the art, and to support the directivity criteria. For instance, the distal opening area may be larger than the proximal opening area. In general, the larger the distal opening **630**, the more control on directivity.

The LF waveguide **620** may float in front of the LF driver **608**. A floating waveguide is not physically connected to its corresponding driver, but rather is detached from the LF driver. As illustrated in FIG. **6**, the proximal opening **624** of the LF waveguide **620** may be spaced apart from the LF driver **608** by a distance to define an air gap **632** between the LF driver **608** and the LF waveguide **620**. The air gap **632** may exist at least in part because the proximal opening area of the LF waveguide **620** may be smaller than the radiating surface opening area of the LF driver **608**. Because the radiating surface **612** moves in response to electrical audio signals, the distance between the LF driver **608** and the LF waveguide **620**—and, correspondingly, the size of the air gap **632**—may vary.

By allowing the LF waveguide **620** to float may provide a means to effectively extract the higher frequencies from the radiating surface **612** of the LF driver **608** directly into the LF waveguide **620** (designed to support these frequencies) via the first radiation path **622** without the use of a compression chamber and without forcing all frequencies into the LF waveguide **620**. Accordingly, frequencies not optimum for the LF waveguide **620** may be allowed a different radiation path, such as the second radiation path **626**. Several paths may be necessary for good performance. These additional radiation paths may be created using numerous acoustical elements and are primarily formed to address different frequency regions.

The three waveguides (the LF waveguide **620** and two HF waveguides **618**) may be formed from a triple waveguide body **634**. The loudspeaker **600** may include two internal chambers—a front chamber **636** and a rear chamber **638**. The rear chamber **638** may house the LF driver **608** in a vented box design. The front chamber **636** may be formed by enclosing the space directly in front of the LF driver **608** and behind the LF and HF waveguides. According to one or more embodiments, the front chamber **636** may include as many as seven (7) exit paths for LF acoustic energy. A primary acoustic exit may be the LF waveguide **620** itself, which may be a critical exit for the crossover frequencies via the first radiation path **622**. Other acoustic exits in the loudspeaker **600** may include: a front acoustic exit **640** defined by a front opening **642** in a front surface **644** of the speaker enclosure **606** directly above the LF driver **608**; a bottom acoustic exit **646** at a bottom surface **648** of the speaker enclosure **606**; two side acoustic exits **650** defined by slender openings **652** in side surfaces **654** of the speaker enclosure **606** (see also FIG. **7**); and two rear acoustic exits **656** in a rear surface **658** of the speaker enclosure **606**.

In some embodiments, the LF waveguide **620** may be the only acoustic exit in the front surface **644** of the speaker enclosure **606**, and may therefore be referred to as a front acoustic exit as well. In either case, the front acoustic exit **640** disposed in the front surface **644** may face a target direction, such as the direction of an audience. The rear acoustic exit **656** in the rear surface **658** of the speaker enclosure **606** may be adapted to face the wall surface **602**.

As previously described, the proximal opening **624** of the LF waveguide **620** may be smaller than the radiating surface opening **616** of the LF driver **608**. Floating the LF waveguide **620** may force only a portion of the LF acoustic energy from the LF driver **608** into the LF waveguide **620** via the first radiation path **622**. Rather, the LF acoustic energy may be divided between the LF waveguide **620** via the first radiation path **622** and the other acoustic exits discussed above via at least the second radiation path **626**.

The frequency region just below the effective operation of the LF waveguide **620** can be difficult to maintain in the design. These wavelengths may be small enough to be greatly affected by the obstructions in the front chamber **636** and may also have difficulty aligning to the LF waveguide energy. Three acoustic exits may be primary for these frequencies that are just below the effective operation of the

LF waveguide **620**. They may include the front acoustic exit **640** adjacent to the LF waveguide **620** and the two side acoustic exits **650** on the side surfaces **654** of the loudspeaker **600** (FIG. **7**). The front acoustic exit **640** may provide a very direct radiation path out for the LF acoustic energy on upper edges of the radiating surface **612**. This exit meets the ¼ wavelength requirement for all frequencies produced by the LF driver **608**. The slender side acoustic exits **650** may be very specific to a small portion of LF acoustic energy from left and right rim portions of the radiating surface **612**. Thus, the second radiation path **626** may be further defined by LF acoustic energy radiating around the outer surface **628** of the LF waveguide **620** and exiting the front acoustic exit **640** adjacent the LF waveguide **620** and/or exiting the side acoustic exits **650**.

According to one or more embodiments, the loudspeaker **600** may include a load plate **660** disposed in front of a portion of the radiating surface **612**, such as a bottom portion **662**. Accordingly, the load plate **660** may be disposed adjacent to the proximal opening **624** of the LF waveguide **620**. In this manner, along with the first HF driver **610***a*, the load plate **660** may obstruct a portion of the LF acoustic energy emitted by the LF driver **608**. The load plate **660** may accomplish several important functions. For instance, the load plate **660** may provide a safe landing for acoustical treatment between the waveguides **618**, **620** and the LF driver **608** critical to suppressing crossover energy trapped in the front chamber **636**. The load plate **660** may also prevent LF acoustic energy from directly pressurizing a rear surface **664** of the triple waveguide body **634**. The load plate **660** may provide a third radiation path **666** out of the front chamber **636** and to the rear acoustic exits **656** and/or the bottom acoustic exit **646** by deflecting LF acoustic energy from the bottom portion **662** of the radiating surface **612** of the LF driver **608**. The design may allow rear chamber vents to radiate into the front chamber **636**. Alternatively, the rear chamber vents may radiate directly into free air. FIGS. **6** and **7** specifically illustrate the details of the redirect mechanisms (e.g., the load plate **660**, triple waveguide body **634**, and front chamber enclosure) for LF energy employed in the loudspeaker design.

One or more applications for the loudspeaker product (e.g., professional cinema surrounds) is such that the acoustical energy below the loudspeaker **600** may be the most important (towards audience) and, therefore, a target axis of the loudspeaker may be approximately 30° down from horizontal. In this orientation, and particularly at angles between 30° and 60° down, the loudspeaker exit lag times are similar to the solution simulated in FIG. **5** described above.

FIG. **8** is an interpretive side view of LF energy wave front arrivals illustrating the characteristic behavior of the loudspeaker **600** in the frequency ranges where the loudspeaker acoustic radiation pattern is omnidirectional. The LF acoustic energy exiting the LF waveguide **620**, the front acoustic exit **640**, and the side acoustic exits **650** may be close enough in time (e.g., within **100** microseconds) to act as one arrival, A, forming a first LF energy wave front **870**. Referring back to FIG. **5**, the magnitude of the first LF energy wave front may be approximately 0.80. The corresponding reflections from the wall surface **602** of LF acoustic energy exiting the LF waveguide **620**, the front acoustic exit **640**, and the side acoustic exits **650**, likewise, may act as a second unified arrival, B, forming a second LF energy wave front **872** that lags the first LF energy wave front **870** by a first lag time (t_1). As noted in FIG. **5**, the magnitude of the second LF energy wave front **872** may be approximately 0.50 and the first lag time t_1 may be approximately 3.70 milliseconds. The LF acoustic energy exiting the rear acoustic exits **656** and the bottom acoustic exit **646** and their corresponding wall surface reflections may all be close enough in time to also act as one arrival, C, forming a third LF energy wave front **874** that lags the first LF energy wave front **870** by a second lag time (t_2). The third LF energy wave front **874** may arrive between the first LF energy wave front **870** and the second LF energy wave front **872** (i.e., $t_2<t_1$). As noted in FIG. **5**, the magnitude of the third LF energy wave front **874** may be approximately 1.65 and the second lag time t_2 may be approximately 1.35 milliseconds. The direct and reflected LF acoustic energy exiting the rear acoustic exits **656** and the bottom acoustic exit **646** act as one unified arrival due to their proximity to the wall surface **602**. Therefore, three major LF energy wave front arrivals may exist—2 source (A and C) and 1 reflection (B)—at these target angles with favorable lag times, mitigating any cancellation notching that occurs in conventional surface-mounted loudspeaker designs.

FIG. **9** is a simplified, exemplary flow chart depicting a method for radiating sound, according to one or more embodiments of the present disclosure. The method may include providing the loudspeaker **600** including the speaker enclosure **606** having a number of acoustic exits, as provided at step **905**. A primary acoustic exit may be the LF waveguide **620**. Other acoustic exits in the loudspeaker **600** may include: the front acoustic exit **640** in the front surface **644** of the speaker enclosure **606**; the bottom acoustic exit **646** at the bottom surface **648** of the speaker enclosure **606**; two side acoustic exits **650** in side surfaces **654** of the speaker enclosure **606**; and at least one rear acoustic exit **656** in the rear surface **658** of the speaker enclosure **606**. The front surface **644** may have at least one front acoustic exit facing the target direction, which may include the LF waveguide **620**, and the rear surface **658** may have at least one rear acoustic exit adapted to face a wall surface **602**.

The method may further include providing the LF driver **608** disposed in the speaker enclosure **606** and adapted to emit LF acoustic energy that exits one or more of the front acoustic exit **640**, the side acoustic exits **650**, the rear acoustic exit **656**, and the bottom acoustic exit **646**, as provided at step **910**. According to one or more embodiments, the method may further include providing the LF waveguide **620** coupled to the LF driver **608**, as provided at step **915**. As set forth above, the LF waveguide **620** may not be physically connected to the LF driver **608** so that only a portion of the LF acoustic energy exits the loudspeaker enclosure via the LF waveguide. The method may also include providing at least one HF driver **610** disposed in the speaker enclosure **606** for emitting HF acoustic energy, as provided at step **920**.

At step **925**, electrical audio signals may be applied to the LF and HF drivers **608**, **610** causing them to produce LF and HF acoustic energy, respectively. At step **930**, the first LF energy wave front **870** may be generated from the LF acoustic energy exiting at least the front acoustic exit **640** and radiating directly in the target direction. The first LF energy wave front **870** may also include LF acoustic energy exiting the side acoustic exits **650** and radiating directly in the target direction. At step **935**, the second LF energy wave front **872** that lags the first LF energy wave front **870** may be generated from the LF acoustic energy exiting the front acoustic exit **640** and reflecting off the wall surface **602**. The second LF energy wave front **872** may also include LF acoustic energy exiting the side acoustic exits **650** and reflecting off the wall surface **602**. At step **940**, the third LF energy wave front **874** that arrives between the first LF energy wave front **870** and the second LF energy wave front **872** may be generated from the LF acoustic energy exiting the rear acoustic exit **656** and radiating directly in the target direction combined with the LF acoustic energy exiting the rear acoustic exit **656** and reflecting off the wall surface **602**. The third LF energy wave front **874** may also include LF acoustic energy exiting the bottom acoustic exit **646** and radiating directly in the target direction combined with the LF acoustic energy exiting the bottom acoustic exit **646** and reflecting off the wall surface **602**.

FIG. **10** is the actual 200 Hz radiation balloon **1000** of the loudspeaker depicted in FIGS. **6** and **7**. Further evidence of the two source arrangement within the loudspeaker **600** is the radiation pattern of the loudspeaker shown in FIG. **10**. The downward tilt in the pattern is not possible with one omnidirectional source. The radiation pattern is a result of the combination of sources presenting two wave fronts which sum together on the downward angles. It should be noted that the radiation balloon was measured with no wall interaction present but does indicate the presence of two sources.

While exemplary embodiments are described above, it is not intended that these embodiments describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention. Additionally, the features of various implementing embodiments may be combined to form further embodiments of the invention.

What is claimed is:

1. A loudspeaker comprising:

a speaker enclosure adapted for surface-mounting and including a front surface having at least one front acoustic exit facing a target direction and a rear surface having at least one rear acoustic exit adapted to face a wall surface; and

a low-frequency (LF) driver disposed in the speaker enclosure and adapted to emit LF acoustic energy that exits at least the front acoustic exit and the rear acoustic exit, the LF acoustic energy exiting the front acoustic exit and radiating directly in the target direction forming a first LF energy wave front, the LF acoustic energy exiting the front acoustic exit and reflecting off the wall surface forming a second LF energy wave front that lags the first LF energy wave front, the LF acoustic energy exiting the rear acoustic exit and radiating directly in the target direction combined with the LF acoustic energy exiting the rear acoustic exit and reflecting off the wall surface forming a third LF energy wave front that arrives between the first LF energy wave front and the second LF energy wave front.

2. The loudspeaker of claim **1**, wherein the first LF energy wave front has a magnitude of 0.80, the second LF energy wave front has a magnitude of 0.50 and lags the first LF energy wave front by 3.70 milliseconds, and the third LF energy wave front has a magnitude of 1.65 and lags the first LF energy wave front by 1.35 milliseconds.

3. The loudspeaker of claim **1**, wherein the speaker enclosure further comprises at least one side surface having a side acoustic exit, the LF acoustic energy exiting the side acoustic exit and radiating in the target direction forming part of the first LF energy wave front, the LF acoustic energy exiting the side acoustic exit and reflecting off the wall surface forming part of the second LF energy wave front that lags the first LF energy wave front.

4. The loudspeaker of claim **1**, wherein the speaker enclosure further comprises a bottom surface having a bottom acoustic exit, the LF acoustic energy exiting the bottom acoustic exit and radiating directly in the target direction combined with the LF acoustic energy exiting the bottom acoustic exit and reflecting off the wall surface forming part of the third LF energy wave front that arrives between the first LF energy wave front and the second LF energy wave front.

5. The loudspeaker of claim **1**, further comprising:

an LF waveguide coupled to the LF driver defining a first radiation path for the LF acoustic energy, wherein the at least one front acoustic exit includes the LF waveguide.

6. The loudspeaker of claim **5**, wherein the at least one front acoustic exit includes a front opening in the speaker enclosure above the LF waveguide.

7. The loudspeaker of claim **6**, the LF waveguide having a proximal opening positioned adjacent to the LF driver and extending away from the LF driver to a distal opening to define the first radiation path therethough, the proximal opening having a proximal opening area that is smaller than a radiating surface opening area to define a second radiation path for the LF acoustic energy around the LF waveguide and out the front opening.

8. The loudspeaker of claim **7**, further comprising:

a load plate directly in front of a bottom portion of the radiating surface and adjacent the LF waveguide to deflect a portion of the LF acoustic energy along a third radiation path to the rear acoustic exit.

9. A loudspeaker comprising:

a speaker enclosure including a front surface having a front acoustic exit, at least one side surface having a side acoustic exit, a rear surface having at least one rear acoustic exit, and a bottom surface having a bottom acoustic exit;

a low-frequency (LF) driver disposed in the speaker enclosure and having a radiating surface adapted to emit LF acoustic energy and a radiating surface opening defined by an outer circumference of the radiating surface;

an LF waveguide defining a first radiation path for the LF acoustic energy, the LF waveguide having a proximal opening positioned adjacent to the LF driver and extending away from the LF driver to a distal opening to define the first radiation path therethough, the proximal opening having a proximal opening area that is smaller than a radiating surface opening area to define a second radiation path for the LF acoustic energy around the LF waveguide and out the front acoustic exit and the side acoustic exit; and

a load plate directly in front of a bottom portion of the radiating surface and adjacent the LF waveguide to deflect a portion of the LF acoustic energy along a third radiation path to the rear acoustic exit and the bottom acoustic exit.

10. The loudspeaker of claim **9**, wherein a target axis of the loudspeaker is approximately 30° down from horizontal.

11. The loudspeaker of claim **9**, wherein a target axis of the loudspeaker is between 30° and 60° down from horizontal.

12. The loudspeaker of claim **9**, further comprising at least one high-frequency (HF) driver disposed in the speaker enclosure.

13. The loudspeaker of claim **12**, wherein the at least one HF driver comprises a first HF driver coupled to a first HF waveguide and a second HF driver coupled to a second HF waveguide.

14. The loudspeaker of claim **13**, wherein the LF waveguide, the first HF waveguide, and the second HF waveguide are formed from a triple waveguide body.

15. A method for radiating sound comprising:

providing a speaker enclosure including a front surface having at least one front acoustic exit facing a target direction and a rear surface having at least one rear acoustic exit adapted to face a wall surface;

providing a low-frequency (LF) driver disposed in the speaker enclosure and adapted to emit LF acoustic energy that exits at least the front acoustic exit and the rear acoustic exit;

generating a first LF energy wave front from the LF acoustic energy exiting the front acoustic exit and radiating directly in the target direction;

generating a second LF energy wave front that lags the first LF energy wave front from the LF acoustic energy exiting the front acoustic exit and reflecting off the wall surface; and

generating a third LF energy wave front that arrives between the first LF energy wave front and the second LF energy wave front from the LF acoustic energy exiting the rear acoustic exit and radiating directly in the target direction combined with the LF acoustic energy exiting the rear acoustic exit and reflecting off the wall surface.

16. The method of claim **15**, wherein the first LF energy wave front has a magnitude of 0.80, the second LF energy wave front has a magnitude of 0.50 and lags the first LF energy wave front by 3.70 milliseconds, and the third LF energy wave front has a magnitude of 1.65 and lags the first LF energy wave front by 1.35 milliseconds.

17. The method of claim **15**, wherein providing a speaker enclosure further comprises providing the speaker enclosure including at least one side surface having a side acoustic exit.

18. The method of claim **17**, wherein generating a first LF energy wave front comprises generating the first LF energy wave front from the LF acoustic energy exiting the front acoustic exit and side acoustic exit and radiating directly in the target direction.

19. The method of claim **17**, wherein generating a second LF energy wave front that lags the first LF energy wave front comprises generating the second LF energy wave front from the LF acoustic energy exiting the front acoustic exit and side acoustic exit and reflecting off the wall surface.

20. The method of claim **15**, wherein providing a speaker enclosure further comprises providing the speaker enclosure including a bottom surface having a bottom acoustic exit; and

wherein generating a third LF energy wave front that arrives between the first LF energy wave front and the second LF energy wave front comprises generating the third LF energy wave front from the LF acoustic energy exiting the rear acoustic exit and the bottom acoustic exit and radiating directly in the target direction combined with the LF acoustic energy exiting the rear acoustic exit and the bottom acoustic exit and reflecting off the wall surface.

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